

Citation for published version:

Palumbo, M, McGregor, F, Heath, A & Walker, P 2016, 'The influence of two crop by-products on the hygrothermal properties of earth plasters', *Building and Environment*, vol. 105, pp. 245-252.
<https://doi.org/10.1016/j.buildenv.2016.06.004>

DOI:

[10.1016/j.buildenv.2016.06.004](https://doi.org/10.1016/j.buildenv.2016.06.004)

Publication date:

2016

Document Version

Peer reviewed version

[Link to publication](#)

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The influence of two crop by-products on the hygrothermal properties of earth plasters

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Abstract

The incorporation of natural fibres in earth construction elements is a common practice that is found both in traditional and in contemporary building systems. The positive effect that such materials have on the mechanical properties of the clay mixtures has been established in previous research. However, their effect on the hydric and thermal properties is less well understood and these properties are important for thermal mass and passive humidity control in buildings, aspects linked to occupant health and reductions in energy use. The present paper includes the first in-depth study of the thermal conductivity and diffusivity, as well as the water vapour permeability and moisture buffering of compressed earth blocks and plasters incorporating natural fibres. Two different vegetable materials, barley straw and corn pith, were mixed to the clay materials in two different percentages (1% and 2%). The results show that the vegetable materials have a great impact on the thermal properties and the apparent density of the mixtures, but a limited effect on the hydric properties. The greatest improvement of the moisture behaviour was shown by the specimens incorporating 2% of corn pith. This improvement is greater for short time exposure than long time exposure. After 3h, these mixtures adsorbed 15.5 g of moisture more than the plain samples, but after 8h the difference was reduced to 8.0 g. This indicates that such mixtures might be more appropriate in environments with short and intense moisture loads, such as bathrooms. Previous research has demonstrated that earth provides the highest moisture buffering capacity of common building materials, and this research demonstrates how these properties can be enhanced for specific applications.

Keywords: clay plaster, CEB, pith, straw, moisture buffering, thermal conductivity.

1. Introduction

A common practice in earth building construction is to add natural fibres to the soil. Typical examples are adobes, cob in the south-west of England or terre/paille and bauge in France. Adding fibres to the soil have several advantages: first, they reduce shrinkage cracks, which is particularly important for plasters; second, they increase the compressive strength; and finally, they improve the

thermal insulation properties [1–5]. The addition of fibres has been reported to influence the equilibrium moisture content and the dynamic moisture buffering properties but little information is available determining the extent of such influence, which is highly dependent on the kind of fibre added to the plaster. Lima and Faria [6] analysed six different clay mortars in which oat straw fibres or typha fibre wool had been added in different proportions. Their results indicate that the addition of fibres has little influence on the moisture adsorption and desorption of the plasters. In a study conducted by Ashour *et al.* [7] three different fibres were added to a soil for the preparation of earth plasters. The fibres consisted of wood shavings, wheat straw and barley straw. The barley straw showed the strongest influence on the equilibrium moisture content. The increase in equilibrium moisture content for a relative humidity (RH) between 40% to 80% was in order of 1% to 3% towards the higher RH levels. In Maddison *et al.* [8], samples of clay plasters mixed with cattail's wool (Typha) and chips of cattail and reed (Phragmites) were subjected to a sudden change in RH from 50% to 80% in order to compare their moisture sorption capacity. The mixtures incorporating the fibres showed an enhanced moisture adsorption up to 24.5% after 12 hours of exposure. However, the kinetics of moisture sorption was dependant on the kind of fibre incorporated. The addition of cattail wool resulted in the most significant increase of moisture adsorption after 1h. However, the moisture adsorbed after 12h was similar or even lower than plain samples. On the other hand, the addition of cattail chips had a lower effect on the moisture absorption after 1h, but presented the best results after 12h.

This increase in EMC which in turn modifies the moisture capacity of the material could have a beneficial influence on the dynamic moisture adsorption or moisture buffering capacity. The moisture buffering capacity of a material is related with its ability to moderate variations in the relative humidity of its surrounding environment. High indoor air relative humidity causes discomfort and might lead to low indoor air quality, as it is related with the propagation of biotic hazards such as moulds and dust mites [9]. Low air relative humidity causes dryness of the mucous in the respiratory tracts and discomfort. In homes, high air humidity is usually the limiting factor determining the minimum sanitary ventilation rates. The control of moisture extremes has positive effects on indoor air quality and might enable a reduction in the ventilation rate and thus, a reduction in heat losses due to air renovation [10–12]. In the frame of the NORDTEST Project [13] and the Japanese Industrial Standard JIS A 1470-1 [14], a useful index was introduced to quantify the moisture buffer capacity of a material in conditions of surrounding humidity variation. The Moisture Buffer Value (MBV) indicates the amount of water vapour that is transported in or out of a material, during a certain period of time, after a controlled variation of relative humidity on one face of a sample. Such an index is included in the international standard ISO 24353 [15].

The water vapour permeability and the thermal conductivity and diffusivity are other material properties that play a role in moist related indoor air quality. These properties have influence on the risk of interstitial condensations, which results in health problems and causes damages on the building structure. They also affect the quality of the thermal envelope, which has been found to be too a driven factor for the propagation of moulds and dust mites in indoor environments [9].

The effect of bio-based materials in the water vapour permeability and moisture buffering capacity of clay building materials was investigated in this study using a series of compressed earth blocks and earth plasters. Earth blocks were prepared with variable contents of barley straw fibres, while earth plasters were also prepared with the addition of a varying content of barley wool and corn pith granulate. In particular, the experimental work was focused on determining how the composite's properties were affected by the combined effect of the addition of vegetable materials, the nature of soil's composition and the manufacturing process. It was anticipated that the fibres would increase vapour permeability as well as moisture capacity by transferring moisture along fibres on the soil/fibre interface and through the body of the fibres. In the case of the granular materials, it is possible that a similar effect is observed, due to the high hygroscopicity of the fibres compared with granular aggregates and to the fact that their incorporation results on a significant reduction of the bulk density of the mixtures, thereby providing more available volume for water to fill. However, it was uncertain to what extent this effect was going to occur and how the fibres would affect the evolution of the moisture buffering capacity by time, i. e. the short and long term moisture sorption.

2. Materials

The organic materials used in this study were barley straw fibres shredded to two different fibre lengths and corn pith aggregates. Barley straw was unbaled and ground. Part of the straw broke down into short and fine fibres that were sieved through a 0.5 mm diameter sieve. Part of the straw just broke longitudinally forming longer fibres that tended to tangle together in a woolly ensemble. Both shapes (short and long fibres) were used. Corn stalks were harvested and dried at room temperature for a week. Then the external peel was manually removed and the corn pith was ground and sieved to 1,0 mm size. The macrostructure of these materials is shown in Figure 1.



Figure 1. Vegetable materials used in mixtures. Barley straw 2 mm (left), barley wool containing longer fibres (centre) and corn pith granulate of 1.0 mm (right).

Moreover, barley straw and corn pith also present important differences regarding their microstructure, which is clearly visible on SEM-images (see Figure 2). Barley straw is formed by a mixture of parenchymatic cellules and several vascular bundles of fibrous structure. The total thickness of the cellular wall and the plasma membrane of the parenchymatic cellules is about $0.6\text{ }\mu\text{m}$, with an intercellular space of diameter about $3\text{ }\mu\text{m}$. On the other hand, corn pith is mainly formed by parenchymatic cellules, as the vascular bundles are removed with decortication. This fact explains that shredded particles are fibrous shaped in the case of barley and granular in the case of corn pith. The cellules of corn pith are larger, with thinner walls and bigger intercellular spaces, which results in a higher macro-porosity [16].

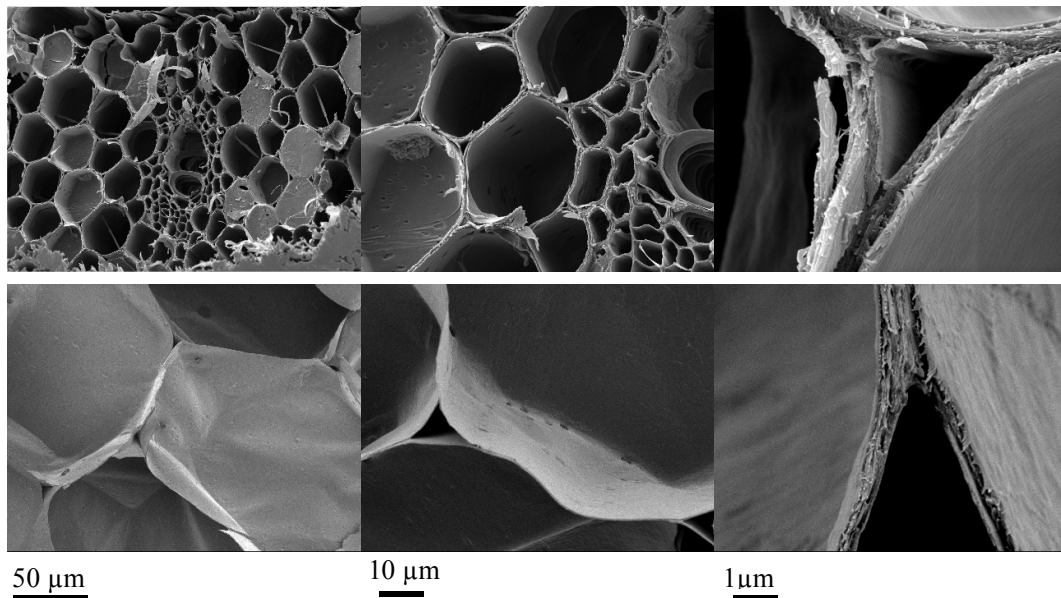


Figure 2. SEM images of barley straw (top) and corn pith (bottom) presented at the same scales.

The soil used for the plasters and the compressed earth blocks (CEB) differed in its composition. The soil used for the plasters was obtained from a commercial earth plaster available in the UK. It was composed by 20% of a fine fraction of clay and silt, 74% of sand and 6% of gravel. The soil used for the CEB was artificially prepared in the laboratory with a ground commercial kaolinite to form the clay sized portion, silt obtained from the sieving of an available soil and commercially available silica based sand. The mixing proportions to obtain a coherent sample were 25% of clay, 20 % of silt and 55% of sand. The soils were analysed with x-ray diffraction in order to obtain the chemical composition of the fine and coarse fractions. This is presented in Table 1, together with the maximum particle size of the coarse fraction and the Atterberg limits corresponding to the fine fraction. The particle size distribution and the aspect of the gravel fractions of both soils are presented in Figure 3.

Table 1. Composition of the soils used.

		Plasters	CEB
Colour		Brownish red	White
Coarse fraction	Particle size (mm)	2	1
	Composition	Quartz	Quartz

Fine fraction	Clays	Cronstedtite ($\text{Fe}_3(\text{Si,Fe})_2\text{O}_5(\text{OH})_4$) (serpentine group),	Kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$) (kaolin group).
		Metahalloysite/Dickite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$) (kaolin group).	
	Silts	Quartz (SiO_2),	Quartz (SiO_2)
		Hematite (Fe_2O_3)	
Atterberg limits	Liquid	56	38
	Plastic	35	27
	Shrinkage	21	11
	Classification	Clay medium plastic	Clay slightly plastic

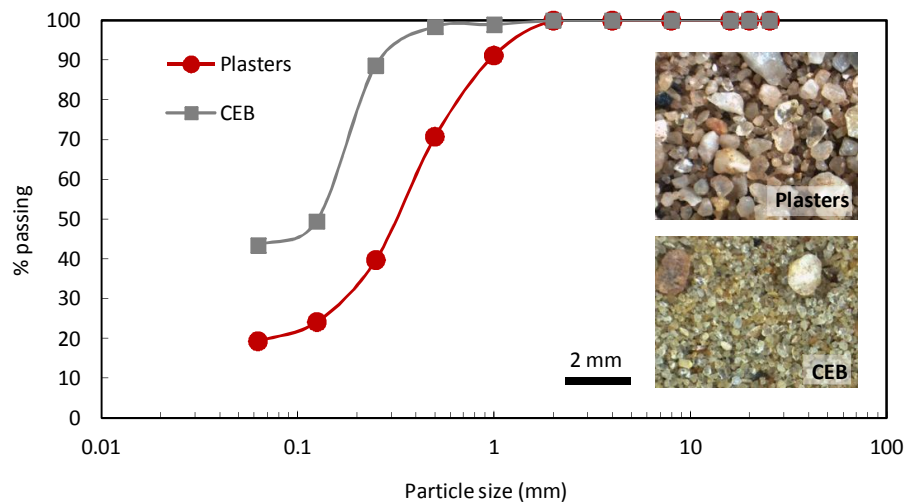


Figure 3. Particle size distribution of the two soils. The aspect of the coarse fractions is presented at the in-set of the figure.

2.1. Sample preparation

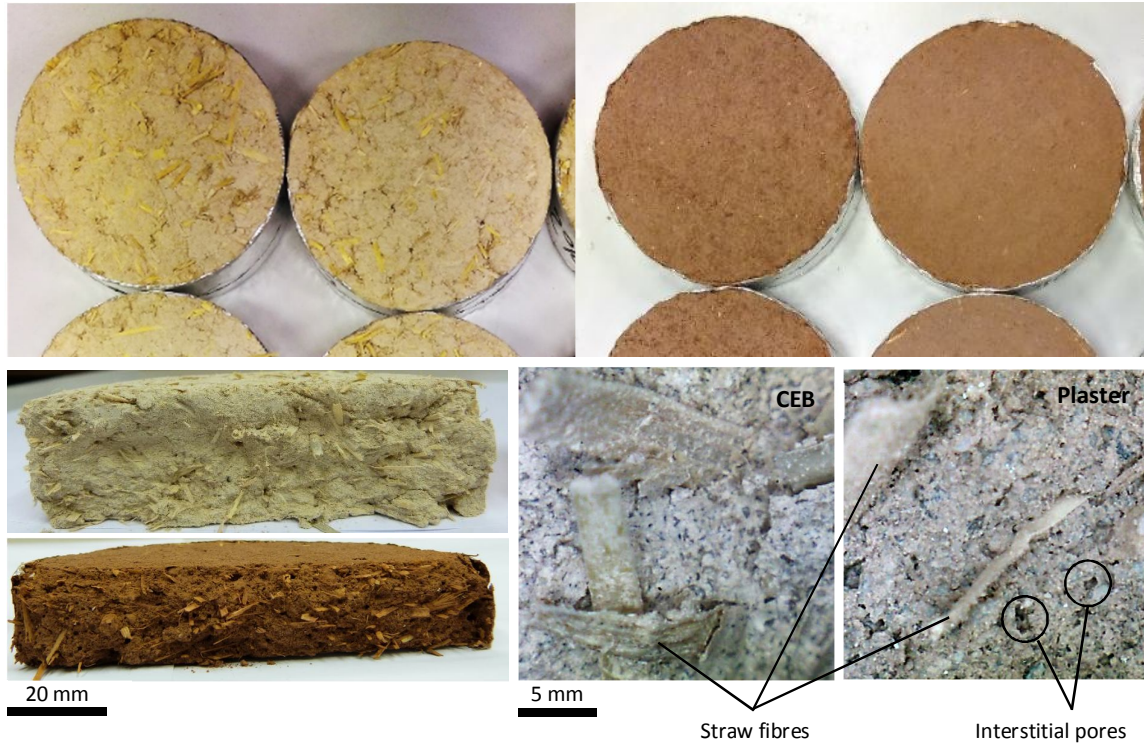


Figure 4. CEB samples and plasters, samples are 100mm in diameter.

Cylindrical compressed earth blocks (CEB) samples of 100 mm diameter and 30 mm thickness were prepared in a plastic sewage pipe used as formwork and compacted with an adapted Wykeham Farrance 50kN triaxial frame. Two different compaction methods were used as it was considered that the addition of straw was very likely to change compaction behaviour. The first method consisted on compacting the samples to a certain volume with known dry mass to obtain the same dry density of 1800 kg/m^3 for each sample (code sd). The second method used a maximum compaction force (of 4.9 kN) in order to identify the influence of adding fibres in a real situation where the compaction force or energy remains constant and the final volume is not controlled (code sc), as with standard test procedures for cohesive soils [17]. The plain sample was compacted at the optimum water content according to EN 13286-2:2010 and the samples with added fibres had additional moisture added until the consistency of the uncompacted material was similar to the plain sample, as determined by visual inspection. As shown in Table 1, no significant difference was observed between the final density of the specimens prepared to reach equal apparent density (sd) and those compacted with an equal

compaction force (sc) and it was not possible to achieve the desired density of 1800 kg/m³ for some of the sd samples as the force required to achieve this was beyond the capability of the compaction equipment. CEB samples containing 0%, 1% and 2% of barley straw were prepared in triplicate using both compaction methods.

The plaster specimens of 100 mm diameter and 20 mm thickness were prepared by adding water until a sufficient workability was achieved for them to be applied with a trowel to a surface. Depending on the fibres, variable water content had to be added, but in general there was an increase in water added for increased fibre content. The specimens were prepared to a constant size, without compaction by smearing the plaster into the mould with a trowel, using a similar action to that for plastering a real wall. The average thickness resulting was 20.7 ±1.3 mm. Plaster samples containing 0%, 1% and 2% of barley straw, barley wool and corn pith were prepared in triplicate. Samples and material properties are summarized in Table 2. The visual appearance of the samples is presented in Figure 3. From the cross section images taken with a binocular magnifying glass, it is possible to distinguish a higher interstitial porosity in plaster samples after drying. From the material data in Table 2, it can be seen that the addition of fibres changes the apparent density of the samples. The plaster without fibres reaches an apparent density of 1848 kg/m³ on average whereas the plaster with 2% of corn stalk only reaches an apparent density of 948 kg/m³ on average. This is expected to greatly influence hydric properties and therefore the moisture buffering value.

Table 2. Description of the tested specimens.

Sample	Description	Apparent density (kg/m ³)	Mixing water (% per dry mass)
C-0	CEB 0% fibre	1896	14
C-sc1	CEB 1% barley straw, same compaction	1818	n.a
C-sd1	CEB 1% barley straw, same density	1770	n.a
C-sc2	CEB 2% barley straw, same compaction	1682	n.a
C-sd2	CEB 2% barley straw, same density	1669	n.a
P-0	Plaster 0% fibre	1848	17
P-bs1	Plaster 1% barley straw	1613	n.a
P-bw1	Plaster 1% barley wool	1541	25.7
P-c1	Plaster 1% corn stalk	1229	39
P-bs2	Plaster 2% barley straw	1400	28.8
P-bw2	Plaster 2% barley wool	1439	30.4

3. Experimental testing

3.1. Thermal conductivity and thermal diffusivity

The thermal conductivity (λ) and thermal diffusivity (α) of the materials was determined, using a surface probe, with the transient electronic thermal analyser Quickline-30, which is designed on the basis of the ASTM D5930 standard. The measurement is based on the analysis of the temperature response of the material to heat flow impulses induced by electrical heating using a resistor heater having a direct thermal contact with the surface of the materials [18]. The advantage of this technique is that it is possible to perform rapid measurements on relatively small samples (down to 60 mm diameter) with accuracy of 5% of reading at temperatures between -20 to 70°C [19–21]. Due to short testing time (typically about 15-20 min), thermal conductivity can be measured assuming a minimal moisture migration through the material, an option not available when using the more conventional guarded hot plate method which requires steady state conditions which will influence the moisture distribution through the sample. The experiments were carried out at room temperature (20°C), in agreement with the specifications of the equipment's manual.

3.2. Water vapour permeability

Water vapour permeability was tested in accordance with the ISO 12572 standard [22]; using the wet cup method. The sample was sealed to the top of a plastic container which contained a saturated salt solution of potassium nitrate to maintain a RH level of 94%. The container was then stored in a TAS (Temperature Applied Science Ltd) environmental chamber maintained at 50% RH and 23°C. To provide a vapour-tight seal around the samples aluminium tape was used as this has provided suitable performance in previous tests [23]. Additionally, a thin bed of silicone was applied to seal the sample to the plastic cup. The water vapour resistance factor (μ) corresponds to the ratio of the water vapour permeability of the sample over the water vapour permeability of air. The water vapour resistance factor has no unit, a water vapour resistance factor of 10, corresponds to a material that has a resistance to water vapour diffusion 10 times greater than the resistance of air in the same conditions.

3.3. Moisture buffering test

The moisture buffering test used the step-response method. This method records the mass variation during RH cycles of a specimen with a known exposed surface area. There are various test protocols currently in use [14,15,23] and all use the same principle of exposing samples to RH

variation over daily cycles and recording the mass change of the sample. The variables considered by the protocols are the time steps, the RH levels, the dimensions of the samples and the surface resistance (associated with the air velocity). The test was performed according to the proposed set up in the Nordtest project [23] which has been used by several authors [24–30]. A climatic chamber was used to set cycles of 8h at high RH and 16h at low RH. The typical test boundary conditions are shown in Figure 54. The mass change was recorded after the samples remained in the chamber for at least 4 cycles as it was noted in previous experiments on earth samples that 4 cycles were sufficient to reach a dynamic equilibrium [31]. The samples with added fibres took longer to reach equilibrium suggesting a different response to the pure soil. The dynamic equilibrium was considered to be achieved when the mass of water at the end of the cycle and the initial mass vary by less than 5%. The mass of samples was recorded outside the chamber to avoid vibration from the ventilation in the chamber and to be able to measure a greater number of samples at the same time. The practical Moisture Buffering Value (MBV_{practical}) is the ratio of mass change per surface area on the relative humidity gradient. Moisture buffering value (MBV) is expressed in $\text{g}/(\text{m}^2\%\text{RH})$ and this single value varies depending on the RH levels and time step used. In the reminder of this article, this test will be referred to as the moisture buffering test.

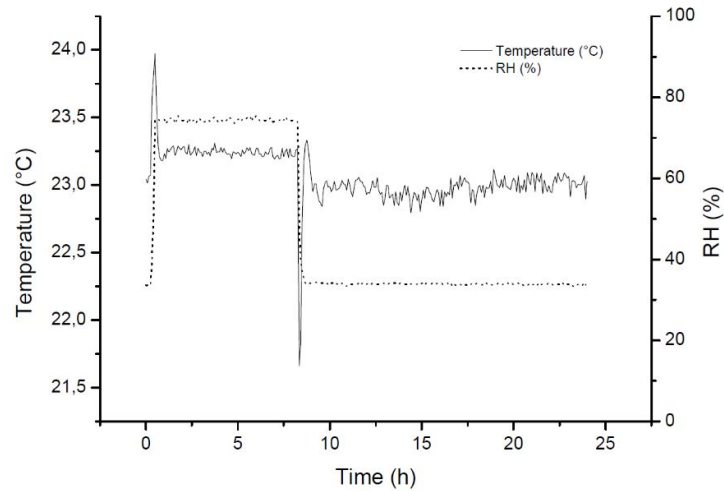


Figure 5 Typical moisture buffering test boundary conditions for a 24h cycle

4. Results and discussion

4.1. Thermal conductivity and thermal diffusivity

The thermal conductivity and thermal diffusivity of the samples was measured in triplicate after storing for at least 28 days at room conditions (50% RH and 20°C). Results are presented in Figure 5. As expected, the thermal conductivity of the clay materials decreases with the addition of the vegetable materials and subsequent reduction in dry density. In the case of CEB samples, results show that the compaction method does not significantly affect the thermal properties of the materials. However, samples made to a same density (sd) present a higher variability in results than those made to same compaction (sc). The thermal conductivity of the samples is reduced in about 25% when the amount of barley is doubled, but the thermal diffusivity is unaffected. In the case of plasters, the incorporation of corn pith resulted in the most significant reduction in thermal conductivity (60% and 78% in average in samples incorporating 1% and 2% of granulate respectively). On the other hand, thermal conductivity was reduced in about 36% and 60% when barley was added at 1% and 2% respectively. No significant differences were observed between the samples incorporating barley straw at different fibre lengths. In Figure 6, the same results are presented as a function to density. For comparison, the results are presented together with those obtained by Minke [32] and Walker et al. [33]. It was observed that the CEB and the plaster samples containing the same amount of barley straw had a similar thermal conductivity (and not higher as expected), despite the fact that the density of the CEB samples is about 15% higher. This might be due to the different soil compositions and particle or pore size distributions. Similarly, it was observed that, for a similar thermal conductivity, the plaster samples incorporating corn pith have a 12% lower density than those incorporating straw, which is probably related to the greater porosity of corn pith.

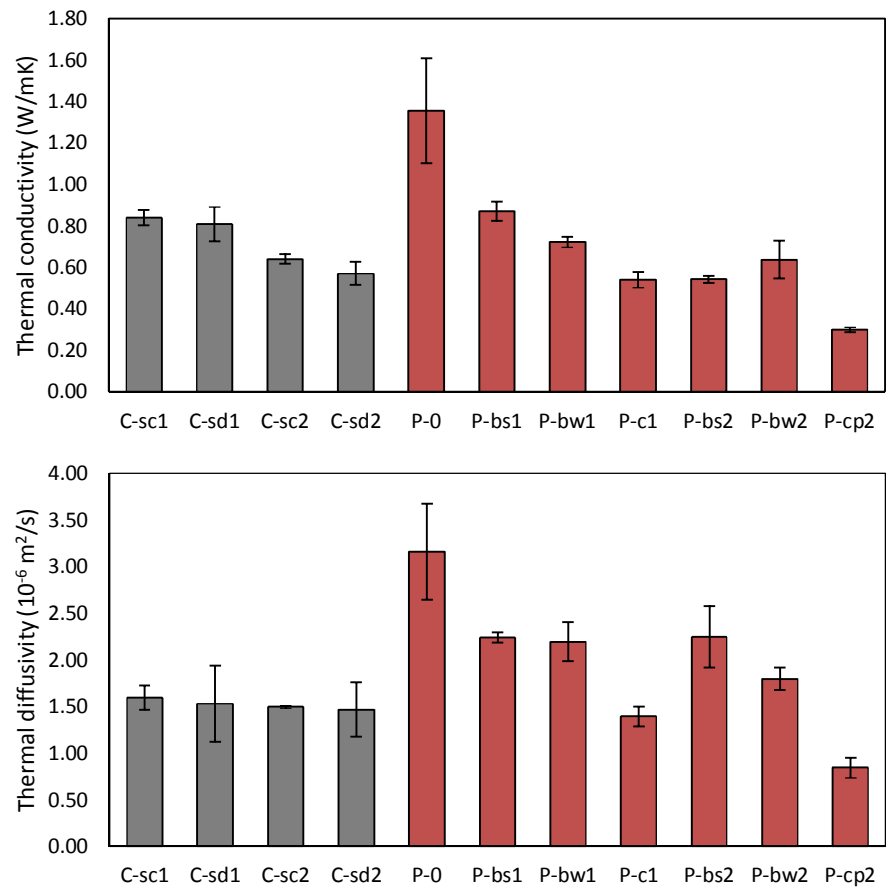


Figure 6. Thermal conductivity (top) and thermal diffusivity (bottom) of the tested samples.

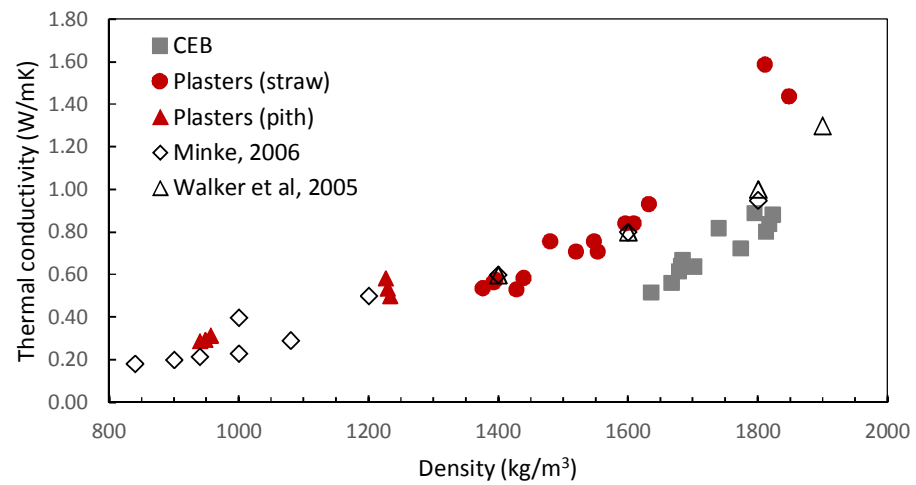


Figure 7. Thermal conductivity of the tested samples as a function of density.

4.2. Water vapour permeability

The results of water vapour permeability tests are presented in Figure 8. The first remark is the great dispersion obtained from the replicates of the plaster specimens, which contrasts with the results obtained for the CEB samples. The dispersion in the case of the plasters was between 9.2% to 22.7%, while in the case of the CEB samples it was up to 6%. No significant differences were found between the two manufacturing methods used for the CEB samples, although again, the dispersion was greater for the samples made to a same density (s.d.). The fact that the dispersion was remarkable only for the plasters and not for the CEB materials, indicates that it might be probably due to the distinct manufacturing process, which induced a higher inhomogeneity of the plaster samples, rather than due to uncontrolled experimental factors. Yet, a slight reduction of the water vapour resistance is observed with the addition of vegetable materials in the case of the earth plasters, especially when corn pith is added. This is not a completely unexpected result as the water vapour resistance factor of the two vegetable materials is lower than that of the earth, in the order of $\mu \sim 3-4$ [16]. On the other hand, the apparent density of corn pith is half that of barley straw. This means that, for the same weigh percentage, the added volume of corn pith is twice that of barley straw, having thus a greater impact on the macro-porosity of the samples. In general, the water vapour resistance of the CEB materials is lower than the plasters, most likely due to the different matrixes used.

In previous work [31], the results of the water vapour permeability test for different CEB and earth plasters were found to be dependent on the apparent density and the amount of mixing water used for sample preparation. However, in this case, the variation of the water vapour resistance factor cannot be explained by the variation of any of these factors because the correlation is very low. This is pictured in Figure 8, where the water vapour resistance factor is plotted against apparent density. Indeed, the incorporation of corn pith results on a remarkably lower apparent density and yet has little impact on the water vapour permeability.

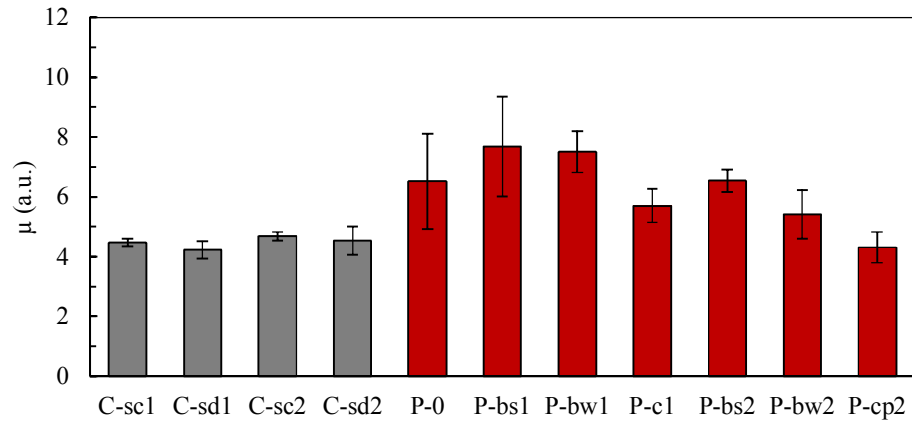


Figure 8. Water vapour resistance of CEB and earth plaster materials.

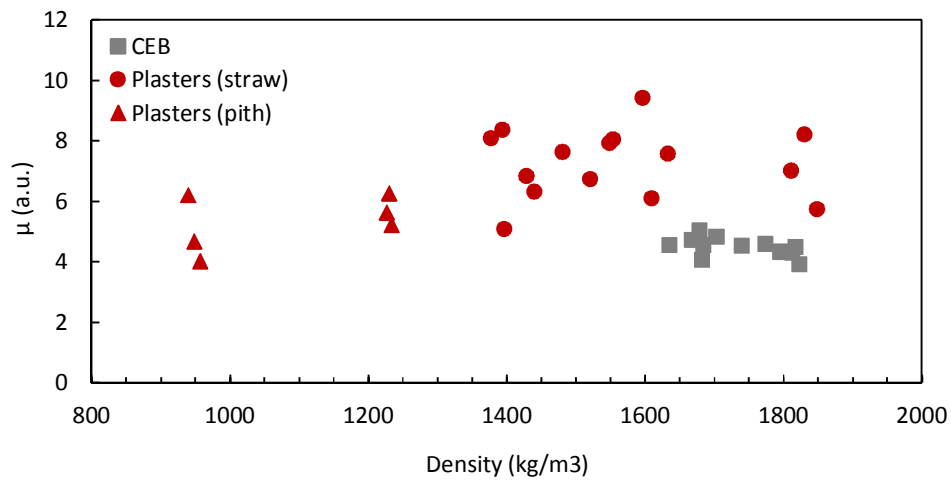


Figure 9. Plot of the water vapour resistance factor against density for the CEB and the earth plaster materials.

4.3. Moisture buffering

From the results it can be concluded that the addition of fibres has a very limited effect on the MBV of both the CEB and the earth plasters. Figure 10 presents the moisture buffering results for CEB samples incorporating 1% and 2% barley straw. For visibility, these are presented in two separated graphics. The Moisture Buffering Value is shown at the inset of the figure expressed in $\text{g/m}^2 \cdot \Delta\text{RH}$. The error shown corresponds to the maximum absolute deviation among the triplicates. The results

are in good agreement and there is very little improvement due to the addition of fibres and no significant difference due to the compaction method.

The moisture buffering of earth plasters performs better than CEBs. The CEBs were prepared with Kaolinite clay, therefore having poor sorption characteristics compared to other clays [34]. The clay minerals in the earth plasters was not determined but the results indicate the presence of clay with strong sorption capacities, especially when considering that the clay sized particle content in the plaster is very low (plaster has a clay and silt sized fraction of 10% whereas the CEB has a clay

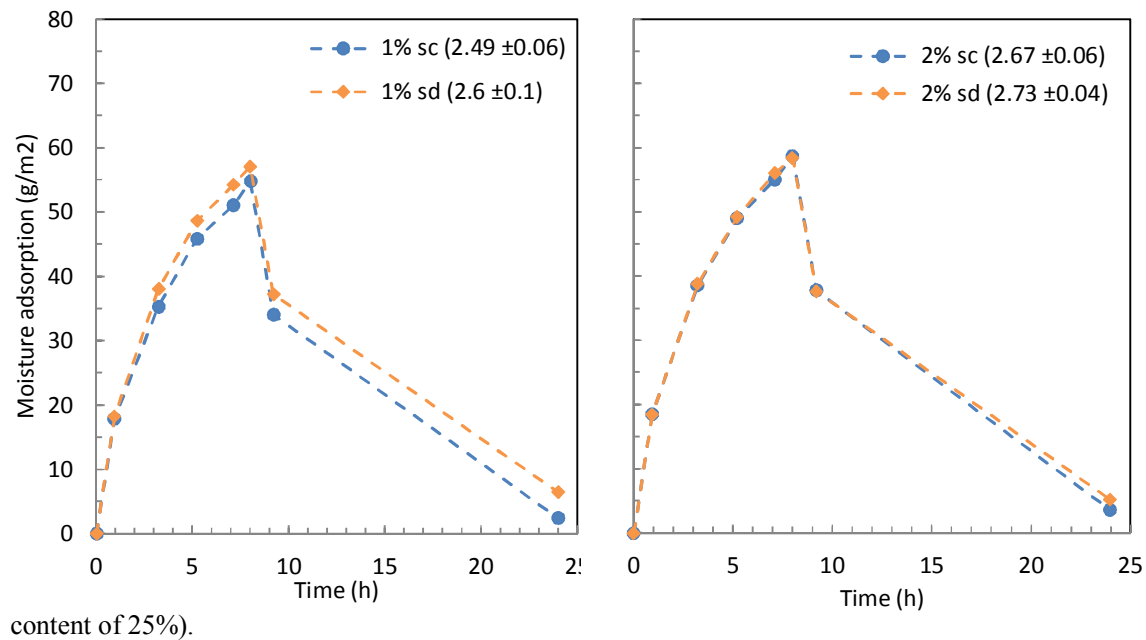


Figure 10. Moisture buffering of CEB containing 1% (left) and 2% (right) barley straw.

The results of the tests on samples with barley straw, barley wool and corn pith are shown in **Error! Reference source not found.** The Moisture Buffering Value is shown in the figure legend expressed in $\text{g/m}^2 \cdot \Delta\text{RH}$. The error shown corresponds to the maximum absolute deviation among the triplicates. In general, the addition of the vegetable materials has little impact on the moisture buffering of the mixtures. Still the trends can be observed, indicating a greater improvement of the moisture buffering when corn pith is added. For improved readability, the impact of the addition of the vegetable materials is compared to reference plain samples in Figure 12. This indicates some interesting trends as the adsorption at the early stage is improved in all cases by the addition of fibres. This is the most evident in the sample with 2% of corn pith (P-cp2) where after 1 hour at 75% RH

(increased RH) the difference in adsorption compared to only earth (P-0) is improved by 11g/m². However, after the first hour, the trends of performance of the different mixtures are distinct. The samples with 1% of barley straw (P-bs1) and 1% of barley wool (P-bw1) improve the adsorption in the first hour but then eventually reach lower levels than the samples with no fibre content. The mixtures incorporating 2% of barley straw and barley wool adsorb more moisture than the plain earth samples during the first hour, but this is not maintained longer. The adsorption rate is similar to that of the earth plaster alone for the rest of the cycle. On the other hand, the samples incorporating corn pith show an important improvement in moisture buffering during the first 3 to 5 hours, after when the adsorption rate is lower than that of the earth plaster alone. This results in a reduction of the variation with time. Two remarks can be made from these observations. The first one is that the samples with vegetable materials have a greater penetration depth of moisture and therefore react faster to the RH change, especially in the case of the corn pith. The second is that, in these samples, the equilibrium moisture content will be reached faster (for the same thickness) and therefore perform less well at longer times (the P-0 samples may eventually adsorb more moisture if the cycles are longer). These results are in agreement with the trends presented by Maddison *et al.* [8].

These changes may have implications regarding the use of clay renders in buildings. Mixtures incorporating vegetable materials might be suitable, for instance, in bathrooms, where a shower creates a short but intense increase of moisture load (estimated at 3 l/h or 0.25 litres per shower of 5 minutes). In this case a fast response would be ideal. In the case of a bedroom, where a long but moderate moisture load occurs (about 0.052 l/h and person), a material with higher moisture storage capacity would be preferred (mixtures with less vegetable materials). Therefore, two parameters are needed to describe the sorption dynamics. The MBV characterises the adsorption after 8 hours but lacks the ability to describe the early and later adsorption phases.

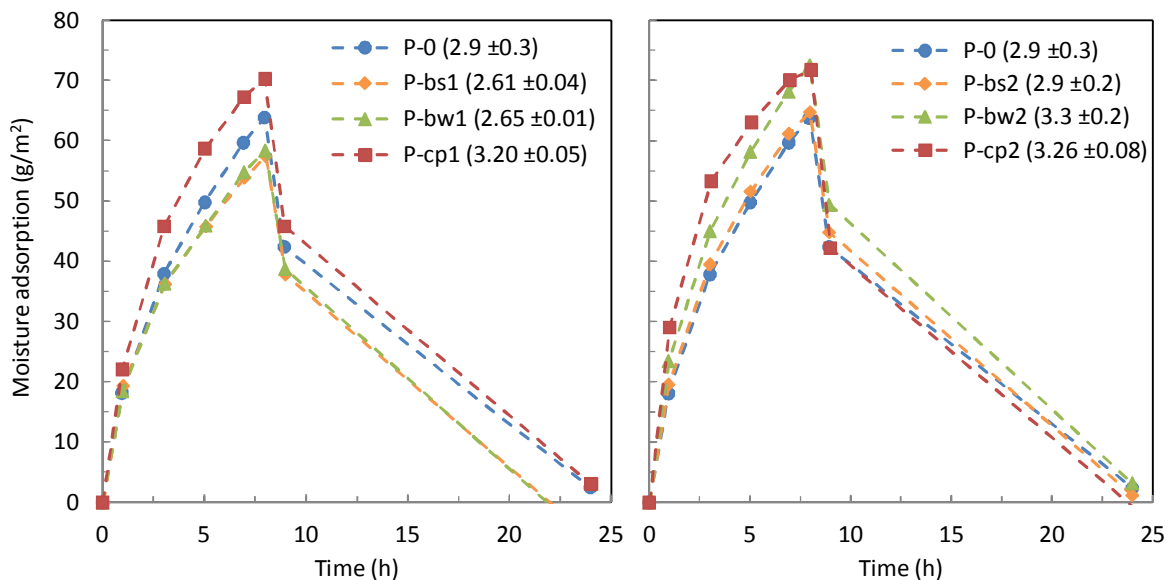


Figure 11. Moisture buffering results of earth plasters

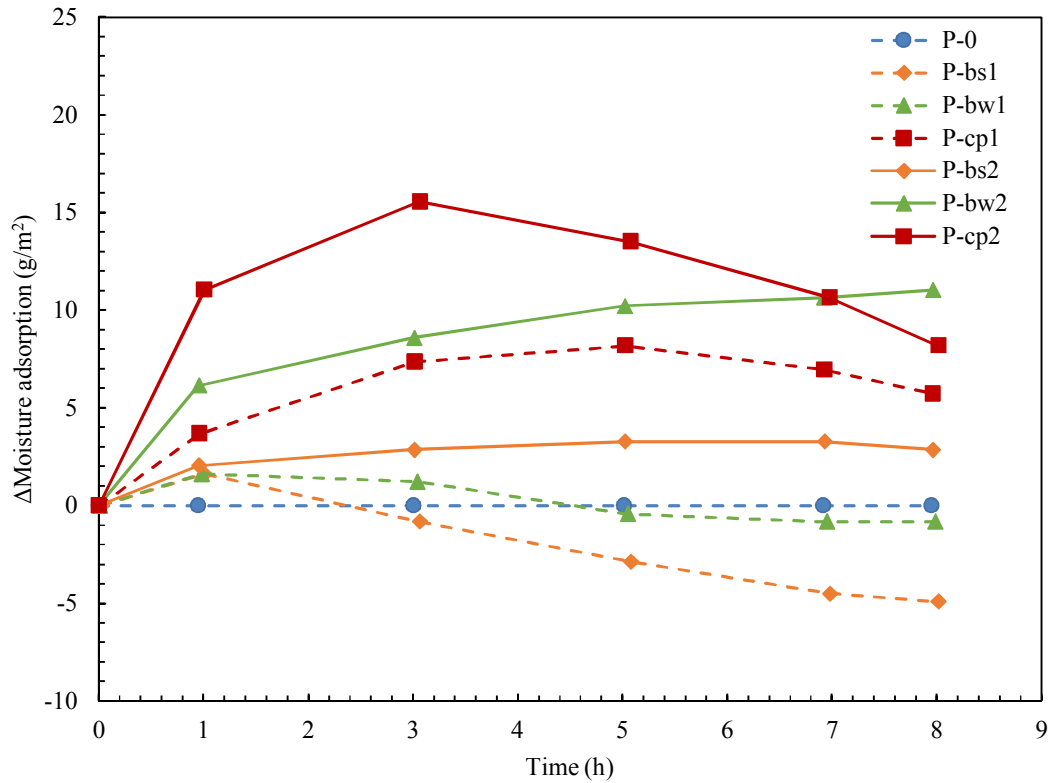


Figure 12. Variation of the performance compared to no fibre content.

5. Conclusion

From the results it appears that the addition of vegetable materials in earth mixtures has much more impact on the density and the thermal conductivity of the materials than on their water vapour permeability and moisture buffering capacity. However, changes were observed for all the parameters analysed, especially in the plaster samples incorporating 2% of corn pith. The incorporation of corn pith results in a 78% reduction of thermal conductivity and a 48% decrease in density. It also results in a moderate increase of the water vapour permeability and the moisture buffering capacity. Similar trends were observed among the CEB and the plaster samples. However, the variability in the results was markedly higher in the later, which indicates a poor homogeneity of the plasters. Although the total moisture adsorbed during the cycles when equilibrium was reached was barely affected by the addition of the vegetable materials, the kinetics of the moisture buffering was clearly affected. This may have implications in terms of the use of the clay renders in buildings. Mixtures incorporating

highly porous vegetable materials such as corn pith might be more appropriate for indoor environments with short and intense moisture loads such as bathrooms.

6. Acknowledgements

Generalitat de Catalunya are thanked for the support provided under the project 2014LLAV00031 and under the PhD studentships FI-DGR. This work is also supported by MINECO (Spain) under the project BIA2014-52688-R. We also acknowledge the help and support of staff and students at BRE CICM, Department of Architecture and Civil Engineering at the University of Bath and the GICITED Research Group

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